Strain Gauge Project

Preliminary Proposal

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DISCLAIMER

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TABLE OF CONTENTS

Contents

1 BACKGROUND

1.1 Introduction

The goal of this project is to build a laboratory strain measurement device. The device is supposed to be multifunctional, which could measure strain under four different load types: axial load, bending, torsion and internal pressure. On top of that, it needs to be accurate and user-friendly enough to reach its educational purposes.

The client and main stakeholder of this project is Dr. David Trevas from the Department of Mechanical Engineering (ME). Having long been teaching the courses of Mechanical Design, Dr. Trevas is not so satisfied with some basic concepts that ME students have upon entering his course, especially with the concept of strain. Currently, the prerequisite course that introduces strain is taught by the Department of Civil and Environmental Engineering (CENE), which Dr. Trevas feels cannot quite meet the needs of ME students. Therefore, Dr. Trevas is keen on developing such a device designed for ME students, which leads to the birth of this project. The project is also sponsored by the Department of Mechanical Engineering.

The device developed in this project will be directly beneficial to ME students, as they will learn the strain measurement process in a way more relevant to their major and make smoother transitions to upper level courses. Also, it will provide great assistance to Dr. Trevas and his colleagues' teaching. Eventually, with new design ideas and budget control added to the device, it is likely to be promoted to elementary and middle schools to boost basic education.

1.2 Project Description

Following is the original project description provided by the sponsor:

"Strain gages are the most important measurement device in mechanical engineering. They are at the heart of digital scales, load cells and pressure transducers. Measurements of force, weight, torque, pressure, stress and strain are routinely made with these tiny inexpensive sensors. While delicate on their own, strain gages are rugged and reliable once they are properly installed. While single gages are useful in some applications, configurations like tees and rosettes can be better in other one. Strain gages are electrical resistors whose resistance varies under strain, and by arranging them in quarter-bridge, half-bridge or full-bridge circuits, we can extract the state of stress observed. This project will build your knowledge and mastery of Strength of Materials (Hooke's Law in 3 dimensions), Circuits (Bridges) and Programming (Data Acquisition using Arduino and the HX711 bridge chip).

The system will also have a data acquisition system and a user's manual that will describe experiments that can be performed with the apparatus. "

2 REQUIREMENTS

Introduction: In this chapter, the team will have a detailed discussion of the project requirements prior to generating design concepts. Starting with the House of Quality table, the team will establish relationships between customer needs and customer requirements. After that, there will be a Black Box Model and a Functional Model respectively to decompose the device according to their functionalities.

2.1 Customer Requirements (CRs)

1. Reliable for experimental use: Measurement error as little as possible.
2. Affordable: The price of the equipment is suitable for most clients and under the budget.
3. Easy to use: Anyone without professional training can quickly become familiar with the use of the device through the product manual.
4. Suitable for different occasions: Can measure four different stresses.
5. Portable: This is laboratory equipment. Need to be easy to bring in and out.
6. Safety: Make sure that no one will be hurt during the operation.
7. Could measure strain accurately: Accuracy is the most important element of the device, and has the highest priority.

2.2 Engineering Requirements (ERs)

1. Maximum Running Cycles: Maximum number of repetitive measurements, Under the premise of ensuring accuracy. The team stipulates that it can reach 100,000 times.
2. Accuracy: The margin of error is 0.5.
3. Load Range: The force that can be measured is in the range of -500N to 500N.
4. Sensitivity: The minimum value of the strain gauge that can be sensed is 1 microstrain.
5. Size: The target size is 2000*2000*500.
6. Device Weight: The max weight of the device is 10 kg.
7. Cost: The total budget of the device needs to be less than $1500.
8. Material Choice: The selected material is Aluminum.

2.3 House of Quality (HoQ)

Table 1: House of Quality

House of Quality (HoQ)										
Customer Need	**Weight**	**Engineering Requirement**	**Maximum Running Cycles**	**Accuracy**	**Load Range**	**Sensitivity**	**Size**	**Device Weight**	**Cost**	**Material Choice**
1. Reliable for experimental use	4		3	9	3	3			3	9
2. Affordable	2		1	3	1	3	3	1	9	1
3. Easy to use	3				3	1	1	1	1	
4. Suitable for different occasions	3			1	1	1				
5. Portable	1						9	9		
6. Safety	3		1				3	1		1
7. Could measure strain accurately	5		1	9	3	9			3	1
Absolute Technical Importance (ATI)			22	90	41	69	27	17	48	46
Relative Technical Importance (RTI)			7	1	5	2	6	8	3	4
Target ER Values			10^5	0.5	500	1	2000*2000*500	10	1200	Aluminum
Target ER Units			cycles	Error%	N	microstrain	mm^3	kg	$	
Tolerances of ERs			±10^4	±0.1	±50			±2	±300	
Testing Procedure (TP#)			Fatigue							

Our team set 7 customer requirements and 9 ERs, through our research and conclusion by ourselves. CRs mainly include the measurement must be reliable and accurate; it should be easy to use and carry; and the device should be inexpensive and should be safe enough. Among them, accurate measurement is the most important CR, followed by the reliability and safety of the device, and finally, if it is cheap and easy to carry, it will be great.

Our team created the QFD chart to map customer requirements to engineering requirements by evaluating and scoring. You can see the details of the scoring in this slide. And after the calculation, accuracy gets the highest ATI Points which means it is the most important ER. We hope the accuracy of the equipment can reach an error of less than 0.5%. The second is sensitivity, we hope it should be within 1 microstrain. The ATI scores obtained by the cost and material choice are almost the same. Our team hopes that the cost can be controlled around US$1,200; the best choice of material is aluminum. Overall, what we get from the QFD chart meets our expectations.

2.4 Functional Decomposition

2.4.1 Black Box Model

Introduction: The Black Box Model below (Figure 1) shows that the function of the device is to measure the strain under different load types.

For the material flow, the device is actuated by human adding external load to the load cell. A temporary deformation of the load cell marks the end of a single measurement.

With the actuation of the device, mechanical energy is also put into the system (pneumatic energy for internal pressure strain). Combined with the energy provided by the power supply, they will ultimately turn into the electric potential acting on the Wheatstone bridge circuit, with a small portion becoming internal energy that would be released into the atmosphere.

The electric potential above generates analog signals, which is followed by analog-to-digital conversions. The process is mainly accomplished by HX711 in the electronics section. Also, with a touch screen displaying the results, visual signals are included from the output.

Figure 1: Black Box Model

Discussion: The Black Box Model gives the team a brief idea of the key features of the device and how it functions. On top of this model, the team put everything in detail and therefore generated a hypothesized functional model in the following section.

2.4.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

Introduction: Overall, the functional model of the device (Figure 2) is divided into three sections in an order of material, energy, and signal. At the same time, the model goes through a complete working process of the device and splits the device into different subsystems.

At the top of this model is the material section. It also corresponds with the physical/mechanical parts of the device. The key feature in this section is the load cell (including strain gauges). When the external load/pressure (expressed by "hand") is exerted on the load cell, the load cell deforms. Changes in energy caused by the deformation would lead to the next section of the model.

Next is the energy section. There are two energy sources in this device. One is the mechanical energy generated by "hand", and the other is the electrical energy provided by the power supply on Arduino. The two types of energy would converge into the strain gauge, causing a resistance change. The change itself would alter the electrical energy on the strain gauge, before passing onto the Wheatstone bridge. Meanwhile, a small portion of energy would become internal energy and dissipate into the atmosphere.

The signal flow of the device starts to gain its importance on the Wheatstone bridge. Along with the approach of the energy, the voltage difference could also be recognized as analog signal. With clock signals generated by the following HX711, this part of the signal would turn into digital form, before being read by the Arduino environment. Eventually, a screen will put all the results into display as visual signals.

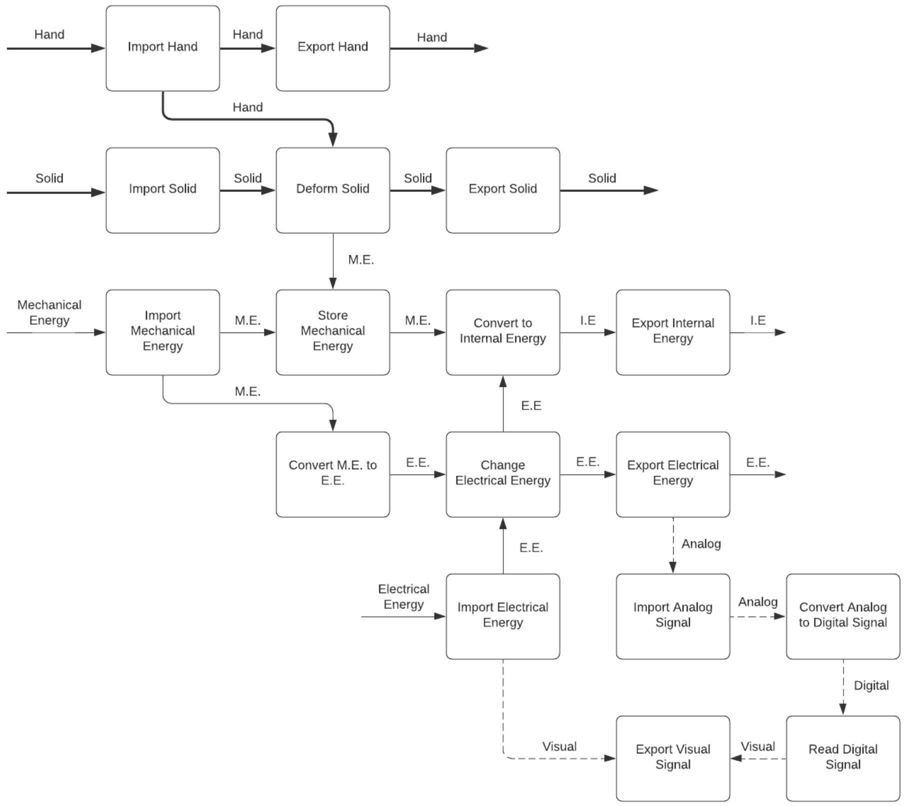


Figure 2: Functional Model

Discussion: The functional model effectively divides the device into five subsystems according to their functionalities: load cell, data acquisition (Wheatstone bridge), data processing (HX711 and Arduino board), serial communication (Arduino program and screen), and assembly (casing). Based on the division on subsystems, the team came up with multiple design concepts in Section 4.

3 DESIGN SPACE RESEARCH

Introduction: The purpose of this chapter is to introduce the literature and benchmarking conducted by each member of the group. That is, search for the professional knowledge and cutting-edge technology of the part of your research on the Internet, engineering literature and journals, and make a simple summary and description at the same time. In the benchmarking section, the existing products on the market are analyzed and compared. This helps our team discover the shortcomings of the preliminary design and make improvements. This satisfies customer needs to the greatest extent.

3.1 Literature Review

In this part, each member is assigned a specific project. They are the circuit part, the axial strain part, bending, torsion, and internal pressure. Each member needs to search for specific examples and formulas to help the team have a fuller understanding of the entire project.

3.1.1 Student 1 (Tianpai Le)

The task of this student features the electronics, including circuits, signal conversions, data acquisition/processing, and Arduino programming. Following is a list of sources used in this aspect.

SparkFun HX711 Guide [1]: An introductory document to the HX711 load cell amplifier. It provides a layout of the circuit wiring around HX711, which was used to carry out Arduino tests.

An HX711 Datasheet [2]: This datasheet features HX711's working mechanism and applications, including the analog-to-digital conversion process using clock signals, as well as an example program driven by Intel MCS-51 which is commonly used in commercial digital scales. The codes were imported as a basis of the final program of the project with some additional adjustments to fit the Arduino environment.

An Arduino-based HX711 Source Program [3]: A program that lists all the hidden functions that will be called in HX711 example programs with explanations. It was used to compare with the program on the HX711 datasheet to fix issues on the newly developed program.

Arduino Cookbook [4]: A comprehensive handbook that introduces all kinds of programs that can be run by Arduino. It was mainly used for writing specific codes on Arduino, where the project "Detecting Light" was referenced for studying pin definition/activation, reading and writing analog/digital signals.

Processing Libraries - Serial [5]: A description of the processing category of "Serial". Used to write relevant codes on Processing to set up serial communication with Arduino.

3.1.2 Student 2 (Ziyu Wei)

The task of this member is to study the relationship between the gauge factor of the strain gauge and the strain of the measured object.The definition of gauge factor is the ratio of fractional change in electrical resistance to the fractional change in length [6]. And for strain gauges of different materials, their coefficients are different [7]. At the same time, in the process of equipment construction, we need to consider many factors to reduce errors, such as the resistance of long wires, the temperature of using strain gauges for a long time, etc. [8]. For Rosette-shaped strain gauges, each gauge is independent of the others, with each gauge having its own Wheatstone bridge circuit. And it is necessary to use the three-dimensional Hooke's law for strain calculation [9]. Finally, for Wheatstone bridges with different structures, our team's equipment needs to use different formulas for strain calculations [10].

3.1.3 Student 3 (Rui Xu)

This team member's task is to research how to use strain gage to calculate bending. From the source [11], he understood the working principle of strain gauge and how to use it. Through the source [12], this team conducted a benchmark test and improved our design on this basis. From Wikipedia [13] he found some principles of bending and some calculation formulas. Then he learned from the source [14] the basic principle about how to install a strain Gauge to measure bending, and how to calculate bending from the Gauge measurement data. From the source [15], he learned about the knowledge of connected circuits and some circuit formulas. In this regard, he studied the knowledge of the circuit in depth, and in the source [16], I understood the difference between the full-bridge and the half-bridge circuit to help us in the final design.

3.1.4 Student 4 (Zhicheng Jiang)

This team member's task is to research how to use strain gage to measure internal pressure. From the website[17] he found the equation between the air pressure and strain, this is the basic part. All subsequent work is carried out around this formula. And from the Micro-Measurements official website[18], there are many ready-made tools and strain gauges, which can be bought and used exclusively. Also, there are many finished products in it, and learning their ideas is also helpful to our own equipment. The Youtube video[19] demonstrates in detail how to measure the pressure in the soda can with a strain gauge, which is the same principle as our equipment. By studying this video, it is very helpful for us to understand the overall process. From the article “Stress Analysis by Using Strain Gages”[20], we can learn the equation of strain gage. And finally, this video[21] shows how to use solidworks to simulate internal pressure. This can help to Simulate the feasibility of our equipment.

3.1.5 Student 5 (Yifan Chen)

Source [22] shows Strain Rosette for Strain Measurement, and the calculation equation of this paste method is effectively displayed. Source [23] introduced Torsional and Shearing Stress Measurement of Axis, which helps to calculate the range of measured values. Source [24] introduced Methods for measuring large shear strains in in-plane torsion tests, which provided some ideas for designing measuring devices. Source [25] shows the mature product on the market and its pricing, which helps the subsequent product design and determines the cost range. Source [26] introduced a method of indirect measurement of torsion, which is helpful for subsequent product design.

3.2 State of the Art - Benchmarking

Based on the original intention and design concept of this project, this team conducts online benchmark tests through extensive research. Since there is no product on the market that is exactly the same as the project we are doing, we compare similar products. Finally, we found the MakerHawk Digital Load Cell Weight Sensor as our benchmark. The product contains a high-precision HX711 module and uses 24 high-precision A/D conversion chips 128 times programmable gain amplifier; load sensor-a sturdy aluminum alloy structure with a strain gauge with pre-connected strain relief wire. Accurately measure the force of 0-5 kg; digital control and serial interface. This is in line with our design requirements. Through the benchmark research, we established the engineering requirements (specific data) and helped us compare and optimize the design in the follow-up process.

4 CONCEPT GENERATION

4.1 Full System Concepts

The team designed two full system concepts after an intense discussion. The two concepts' codenames are "Turntable" and "Puzzle".

4.1.1 Full System Design #1: Turntable

Our first design is this "Turntable" (Figure 3). Four different parts are installed together on a circular base. Obviously, it looks cool, and by turning the dial, you can switch to the desired mode. At the same time, we can use a computer to supply power and display data, this will be easy. But it also has disadvantages. The diameter of the turntable will exceed 1 meter, so it will be troublesome to bring it into the lab. Moreover, the overall dispersion means that we need to equip each group with a set of lines, which will increase the budget.

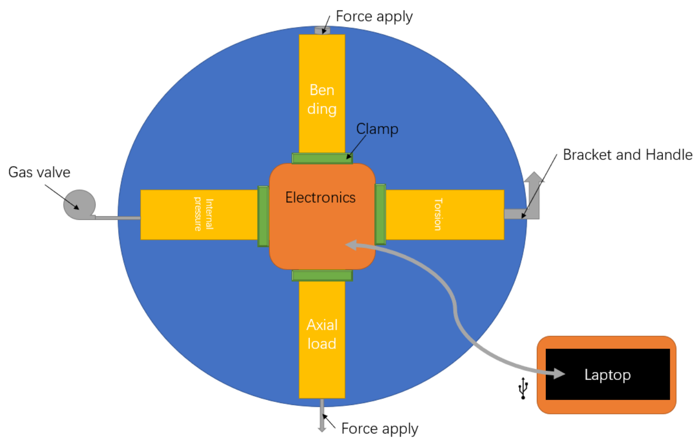


Figure 3: Design Concept - "Turntable"

4.1.2 Full System Design #2: Puzzle

Our second design, the "Puzzle" (Figure 4). The four parts can be disassembled and assembled like a puzzle. The overall volume will be much smaller than before. Moreover, we only use one Arduino to link at the end, which reduces the cost. At the same time, we choose to use batteries for power supply and a single capacitive screen, so that the entire device will be more complete and independent. Although this may seem ordinary, it is very practical. The only flaw is the battery life and the stability of the power supply.

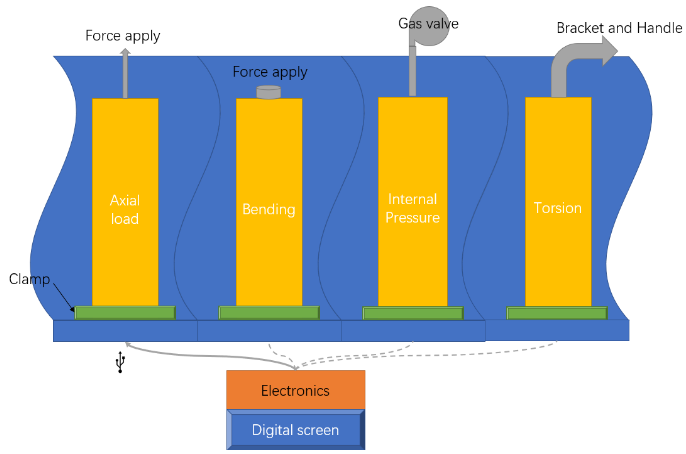


Figure 4: Design Concept - “Puzzle”

4.2 Subsystem Concepts

This section mainly explains the team’s five subsystems (mainly about circuit connection and data processing) and their corresponding designs.

4.2.1 Subsystem #1: Load Cell

The Load cell subsystem includes four different measurements, axial force, bending, torsion and internal pressure (Figure 5). The measurement metal is deformed by applying force in different ways. For the axial force, a pulley is used to convert the vertical pull of the weight into a horizontal pull. For bending, apply vertical gravity at the end points. For torsion, place a handle at the end and use a bracket to counteract gravity. Finally, measure the internal pressure and use an air pump to pump air to the air valve at the end of the hollow metal column.

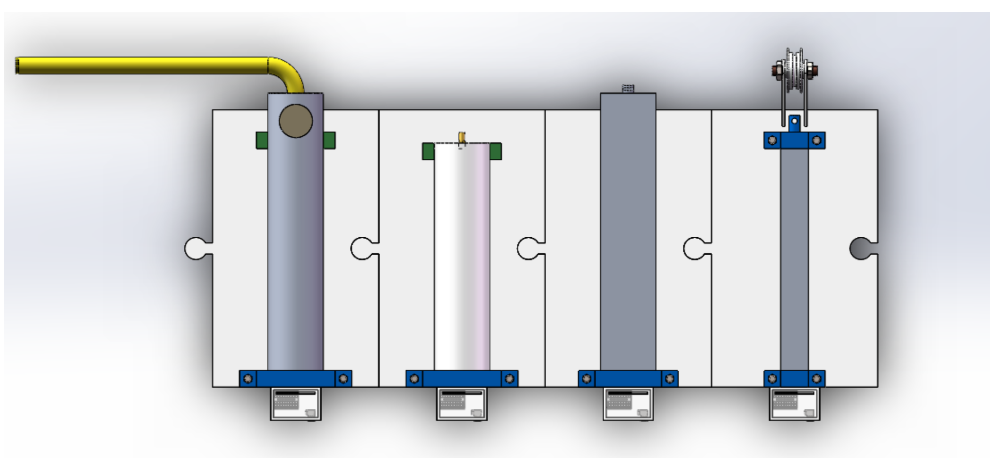


Figure 5: Load Cell Part

4.2.2 Subsystem #2: Data Acquisition

The data acquisition subsystem of the device includes the strain gauge and the Wheatstone bridge circuit (Figure 6). Technically, there is no difference among all design concepts in this subsystem as they share the same circuit layout. The only thing that matters is the selection among quarter bridge, half bridge, and full bridge, depending on the amount strain gauges and resistors in a Wheatstone bridge. The team would prefer full bridges for its high sensitivity and low temperature effects. However, such selection is still independent from design concepts.

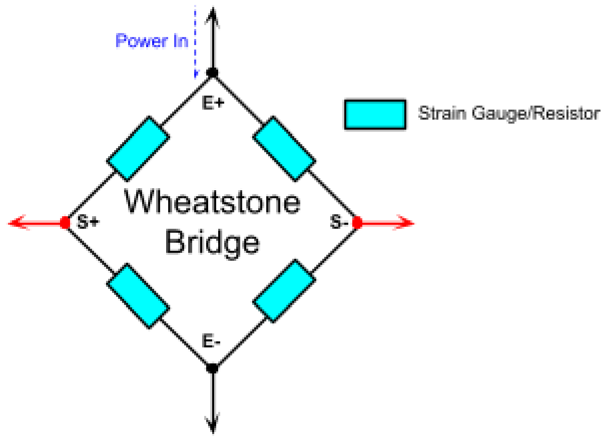


Figure 6: Wheatstone Bridge Circuit

4.2.3 Subsystem #3: Data Processing

This subsystem includes the HX711 load cell amplifier and the Arduino board, with the former performing signal conversions and the latter receiving the outputs. Due to both components being existing products and the circuit connections fixed, there is no room for design variables between them. However, their connections with the subsystem of data acquisition can have more than one approach. In fact, the circuit between them is not supposed to be always closed. Designing a "port" between them will increase the flexibility of the device and reduce electronic components (by sharing the data processing section). Based on that idea, two concepts were designed to make it possible.

4.2.3.1 Design #1: Connection with USB Extension Wires

The first concept makes smart use of USB extension wires (Figure 7). Starting with cutting the wire in halves and peeling out part of the insulation layer, the wires in one half can be soldered to the load cell and the other half soldered to the data processing section. It means the male and female connectors will be separated and therefore forming a complete USB port.

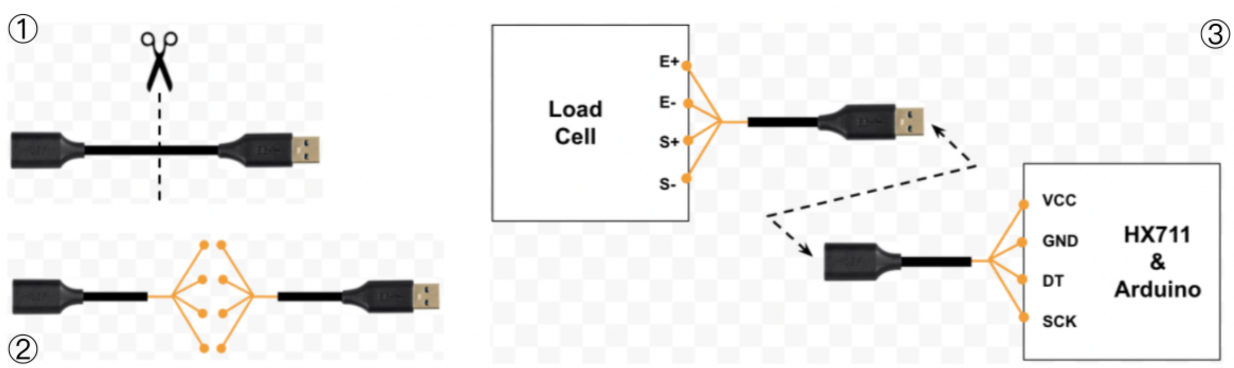


Figure 7: Data Processing - Connection with USB Wires

4.2.3.2 Design #2: Connection with Terminal Blocks

This concept works similarly with the previous one, only replacing USB extension wires by terminal blocks (Figure 8). As a comparison, it has an advantage in terms of technical difficulty, as jumper wires can be directly inserted into the terminal block without soldering. However, they will not be as effective as USB ports. Considering the pros and cons between these two concepts, the team still decides to select USB extension wires for their better fit on a product.

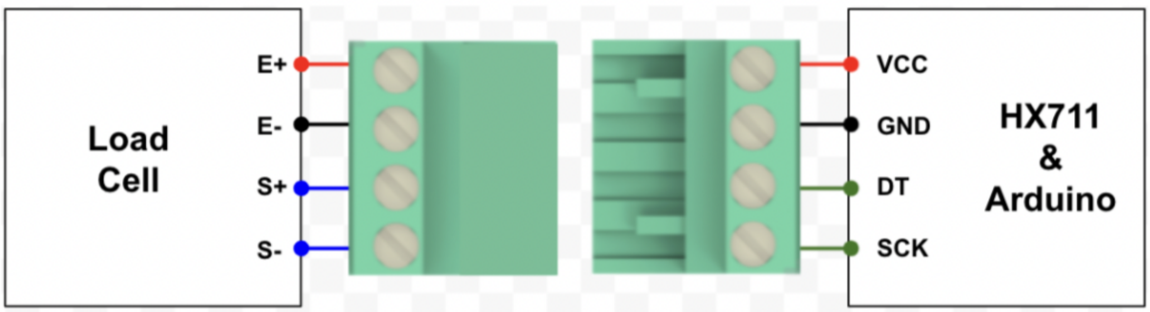


Figure 8: Data Processing - Connection with Terminal Blocks

4.2.4 Subsystem #4: Serial Communication

This section mainly focuses on the Arduino program and a screen. Since the screen hasn't been set up in the team's existing system, the job is currently accomplished by Processing, a programming application which could display graphics. As long as the environment of this subsystem is completely virtual, there is no need to generate design concepts in this part.

4.2.5 Subsystem #5: Assembly

4.2.5.1 Design #1: Assemble from parts

The design plan is to assemble the four measuring parts through a modular design.

4.2.5.2 Design #2: Welding fixed

In order to maintain the shape of the turntable, this design solution requires four measuring devices to be fixed around a central point.

5 DESIGNS SELECTED – First Semester

In this part, our team will discuss how we get our final concept and how it satisfies the requirements.

5.1 Technical Selection Criteria

Table 2: Decision Matrix

Criteria	Weight	Concept 1		Concept 2	
		Score	Weighted Score	Score	Weighted Score
1. Reliable for experimental use	0.19	6	1.142857143	9	1.714285714
2. Affordable	0.10	5	0.4761904762	7	0.6666666667
3. Easy to use	0.14	6	0.8571428571	8	1.142857143
4. Suitable for different occasions	0.14	7	1	7	1
5. Portable	0.05	5	0.2380952381	6	0.2857142857
6. Safety	0.14	4	0.5714285714	4	0.5714285714
7. Could measure strain accurately	0.24	8	1.904761905	8	1.904761905
Sum	1	41	6.19047619	49	7.285714286

In the process of designing the decision matrix, our team mainly considered how well each design meets customer needs. And, we set weights for each customer needs according to their scores. Because our second design is based on the first improvement, so of course, the second design will score higher. It has the following advantages.

1. More portable. It is detachable and more flexible to use.
2. Save costs. Smaller size and fewer accessories means more economical.
3. More independent. No need to rely on a computer to complete the operation.

5.2 Rationale for Design Selection

In this part, our team will use detailed data and equations to show that our design is reliable.

5.2.1 Axial Load

$$\varepsilon_x = \frac{F}{AE} \qquad \varepsilon_y = -v\frac{F}{AE}$$

Equation 1: Strain on x and y axis

Table 3: Axial Load Strain Calculations

Quantity	Definition	Value (Unit)
F	Applied force	100 N
A	Object cross-sectional area	0.00000375 m^2
E	Young's modulus	73.1 Gpa

ν	Poisson's ratio	0.33
ε_x	Strain in x direction	364.8 microstrain
ε_y	Strain in y direction	-120.4 microstrain

5.2.2 Bending

$$\sigma_x = \frac{M_z y}{I_z} \qquad \sigma = \varepsilon \cdot E$$

Equation. 2 Bending Moment and Strain

Table 4: Bending Strain Calculation

Quantity	Definition	Value (Unit)
F	Applied force	100N
E	Young's modulus	73.1Gpa
σ_x	Bending Stress	265.9370725 Microstrain
M_z	Moment about the axis	45 N
y	Distance to the neutral axis	0.45 m
I_z	The second moment of area	0.00000104166667 m^3

5.2.3 Torsion

$$\frac{T}{J} = \frac{G \times \theta}{L}$$

Equation 3: Torque and Stress

$$I_z = \frac{\pi \left(D^4 - d^4\right)}{32}$$

Equation 4: Polar Moment of Inertia

Table 5: Torsion Strain Calculation

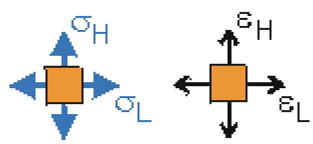
Quantity	Definition	Value (Unit)
T	Torque or twisting moment	49.05 N/m

D	Density	2.78 g/cm³
G	Modulus of rigidity (PanGlobal and Reed's) or shear modulus	26900 Mpa
L	Length of the shaft	0.6 m
D1	Outer Diameter	0.1 m
D2	Inner Diameter	0.098 m

Through the above formula and equation, we can get the size of the rotation angle as 0.8224718592 degrees.

5.2.4 Internal Pressure

According to customer requirements, the force we apply is about 10bar air pressure. According to the following formula, we can calculate the strain.



$$\varepsilon_H = \frac{\sigma_H}{E} - \nu\frac{\sigma_L}{E} = \frac{pR}{Et}\left(1 - \frac{\nu}{2}\right)$$

Equation.5: Strain in vertical direction

$$\varepsilon_L = \frac{\sigma_L}{E} - \nu\frac{\sigma_H}{E} = \frac{pR}{Et}\left(\frac{1}{2} - \nu\right)$$

Equation.6: Strain in horizontal direction

Table 6: Internal Pressure Parameters

Quantity	**Definition**	**Value (Unit)**
p	Pressure	1000000 (N/m^2)
R	Outer Diameter	0.1 (m)
E	Young's modulus	73.1 (Gpa)
t	Width	0.001 (m)
v	Poisson's ratio	0.3333

So we can get the result. ε_H= 569.99544, ε_L= 113.999088. This shows that this design is feasible.

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